Reexamination of Late Holocene Sea-Level Changes in Japan

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Reexamination of Late Holocene Sea-level Changes in Japan

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Abstract In order to restudy the late Holocene sea-level changes in Japan, detailed investigations were made in the following three areas by the following methods respectively.

In Matsushima Bay area situated in the relatively stable zone of crustal movement, changing sea level was reconstructed by tracing the migration course of shoreline in profile. Combination of diatom analysis and radiocarbon dating made the tracing possible. In Nanao-nishi Bay area situated in the uplift zone, it was reconstructed by eliminating the influences of uplift from the relative sea-level change clarified by FeS_2 contents analysis and radiocarbon dating. In Oku-Tokyo Bay area where a bay extended far back during the Postglacial transgression, it was reconstructed by estimating the tidal ranges of the period.

As a result, it was indicated that the highest sea level during Holocene time in Japan occurred in about 3,500 yr B.P., and the sea level at that time stood at 1.0-1.5 m above the present one. Moreover, the sea-level fall around 2,000 yr B.P. was found in Matsushima Bay area. It is considered an eustatic change because the same trend change has been found in wide area including the area of different hydro-isostatic trend.

Key words: sea-level changes, late Holocene, the Japanese Islands, tidal range, crustal movement.

1 Introduction

One of the important factors for environmental changes of coastal area is provided by sea-level changes alike crustal movement, sediment supply fluctuations, and so on. Various small-scale landforms in a coastal plain, for example beach ridge ranges, coastal sand dune ranges, buried shallow valleys and terraces, *etc*., have been formed by complex processes of these factors during Holocene time. For finding the causes of their formation and their development processes, firstly, sea-level changes and sediment supply fluctuations which occur in relatively large scale have to be clarified independently. This paper discusses the sea-level changes during late Holocene time in Japan.

Many studies have discussed the outline of the Holocene sea-level changes in

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Japan since the 1960's as the radiocarbon dating has become popular (Fujii and Fuji 1967, 1982 ; Umitsu 1976 ; Omoto and Ouchi 1978 ; Moriwaki 1979 ; Matsumoto 1984 ; Endo *et al.* 1989, *etc.*). However, the small-scale sea-level changes during late Holocene time, which seem to have affected the formation of the various small-scale coastal landforms, are not yet revealed sufficiently, because they are frequently reconstructed from the age of landforms which are not fully explained in the causes of their formation and from the few direct data indicating the paleosealevel. Moreover, a single sea-level change curve is depicted by using the data obtained from the various areas where the trend of crustal movement is different. Thus, the method and accuracy of the studies are not suitable for the investigation of the late Holocene sea-level changes.

This paper intends to reconstruct the accurate sea-level changes of late Holocene time in Japan. For the purpose, suitable method and study areas are selected at first. As the Japanese Islands are situated on the continental margin away from the area covered by ice sheet during the Last Glacial Stage, it is expected according to the hydro-isostatic theory by Peltier *et al.* (1978), Clark and Lingle (1979), *etc.* that the sea level stood above the present one during a certain period in late Holocene time.

2 Outline of the study areas and methods

The following three areas have been selected for this study ; two valley bottom plains facing Matsushima Bay in the northwestern part of Sendai Bay, a valley bottom plain facing Nanao-nishi Bay in the Noto Peninsula, and alluvial plains facing Tokyo Bay (Fig. 1).

Matsushima Bay and Nanao-nishi Bay are small inner bays. In such areas, suitable sites for field research work to reconstruct small-scale sea-level changes are provided, because changes in the sedimentary environment are expected to be caused

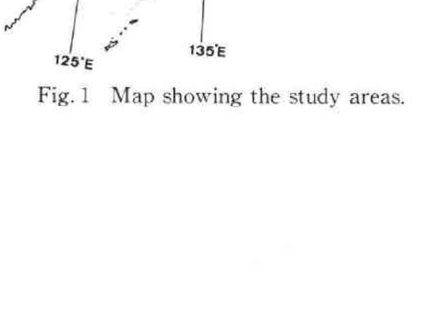


Fig. 1 Map showing the study areas.

simply by sea-level changes ; no disturbance is induced by the development of bars or beach ridges, because wave action and coastal currents are usually too weak to form them.

Judging from the distribution of Pleistcene and Holocene marine terraces and active faults which will be mentioned later, presumably Matsushima Bay area is relatively a stable area of crustal movement, and Nanao-nishi Bay area seems to be an upheaval area. Therefore, if the influences of the crustal movement of Nanao-nishi Bay area would be inferred, the common trend should be found both in the sea-level change in Matsushima Bay area and in the sea-level change after eliminating the influences of the crustal movement in Nanao-nishi Bay area.

On the other hand, in Tokyo Bay area, the Postglacial transgression, which is called '*Jomon* Transgression' in Japan, reached over 140 km inland from the mouth of the bay. The former Tokyo Bay has been called 'Oku-Tokyo Bay'. In such a deep bay, it is possible that the tidal range is considerably amplified than that at the mouth. Though several sea-level change curves have been depicted in this area, e.g., by Kaizuka *et al.* (1977), Endo *et al.* (1989), and so on, the problem of amplified tidal range has not been considered. When paleosealevel is inferred from the upper limit of marine deposit, the problem must not be ignored. Then, the author reconstructed the sea-level changes by considering the tidal range in Oku-Tokyo Bay.

This paper discusses the late Holocene sea-level changes in Japan by comparing the three sea-level change curves reconstructed in the above three areas.

The paleosealevel was determined on the basis of the altitude of the upper limit of marine deposit and its deposited age as a rule. Diatom analysis is a most useful method for determination of the upper limit of marine deposit, because it makes possible to reconstruct the processes of changes of sedimentary environment. The diatom analysis was applied for paleosealevel determination in Matsushima Bay area and Oku-Tokyo Bay area. However, FeS_2 contents analysis was applied in Nanao-nishi Bay area, because diatoms were not found in the valley bottom plain deposits of the area. The deposition ages of the upper limit of marine deposits were determined by radiocarbon dating. In Matsushima Bay area and Nanao-nishi Bay area, successional reconstruction of sea-level changes was tried by tracing the migration course of shoreline indicated by the boundary between marine deposit and fresh-water deposit in profile of each valley bottom plain.

3 Late Holocene sea-level changes in Matsushima Bay

3.1. Regional setting

Matsushima Bay is a small inner bay nearly separated from the open sea (Fig. 2). The bay has only an area of 35 km^2. The alluvial lowlands distribute between hills as

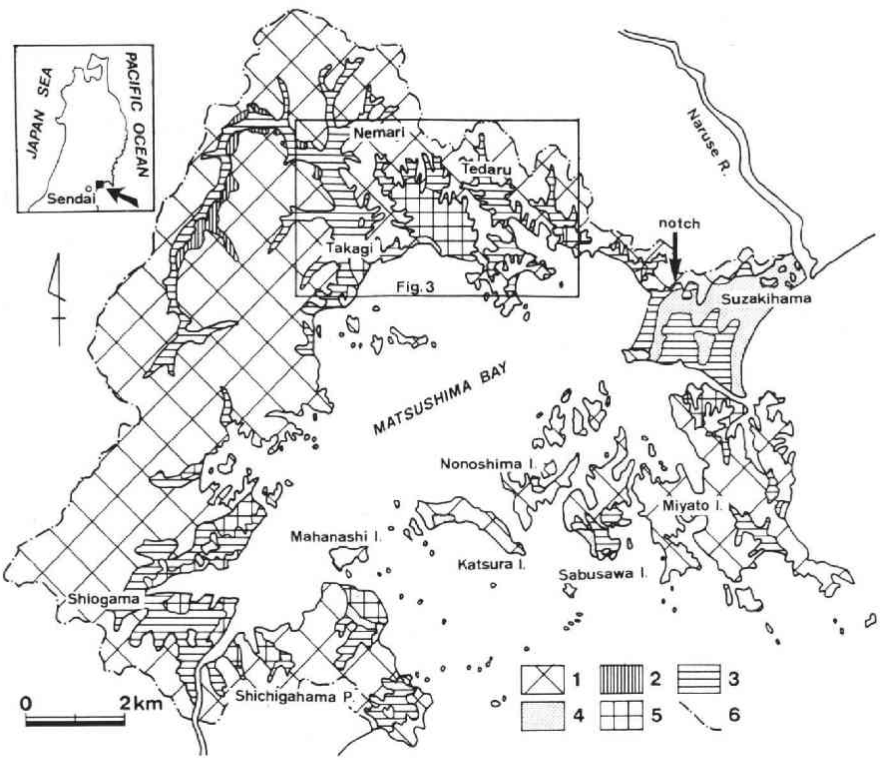


Fig. 2 Geomorphological map of Matsushima Bay including the study area.
1. hills, 2. terrace, 3. alluvial lowland, 4. bar, 5. reclaimed land, 6. watershed of the Matsushima Bay basin.

valley bottom plains. The deposits in the bay are almost muddy one. The wave action is too weak to form bars or beach ridges in front of the valley bottom plains. Therefore, it seems that the sedimentary environment in the valley bottom plains facing Matsushima Bay has changed with transition of relative relationship between sea-level change rate and accumulation rate.

On the other hand, Pleistocene terraces which is 10-15 m higher than the alluvial lowlands are found along the Takagi River. There is a possibility that the terraces were formed during the Last Interglacial Stage, because they don't dip into the deposit of the valley bottom plain and their surfaces are well preserved from erosion. Judging from the relative height between the Pleistocene terraces and the alluvial lowlands, it seems that Matsushima Bay area has been relatively stable on crustal movement during late Pleistocene time. Moreover, geomorphic evidences of crustal movement in Holocene time, for example Holocene marine terraces, active faults and active folds are not found in the coast of Matsushima Bay.

3.2. Study method

The samples for diatom analysis were collected from 10 locations on two valley bottom plains (Takagi-Nemari valley bottom plain and Tedaru valley bottom plain) as indicated in Fig. 3. Diatom species were classified into following three groups according to Kashima (1985), *i.e.*, fresh-water species which live in fresh-water environment only, fresh-brackish water species which live in from fresh-water to brackish-water environment, and marine-brackish water species which live in from marine-water to brackish-water environment. In case of need, FeS_2 contents analysis was applied for estimation of sedimentary environment with diatom analysis. FeS_2 contents analysis was performed after Shiragami (1985). The altitude of sampling site was surveyed by leveling from a bench mark or sea surface.

The samples for radiocarbon dating were mainly collected from the horizon between marine deposit and fresh-water deposit clarified by diatom analysis. Thereby precise recognition of paleosealevel became possible.

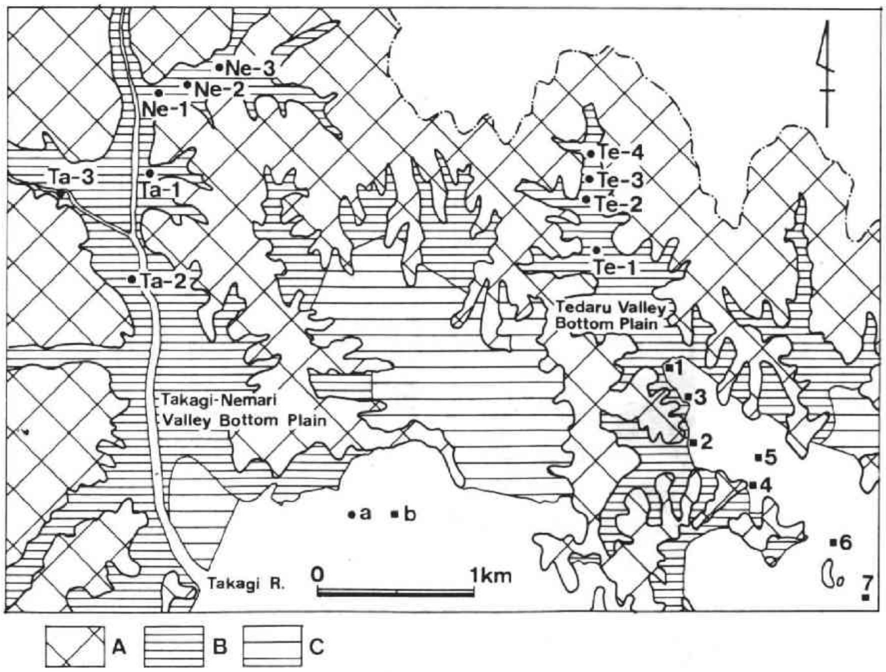


Fig. 3 Map showing the sampling sites for diatom analysis.
a : fossil diatom sampling site, b : living diatom sampling site.
A : hills, B : alluvial lowland, C : reclaimed land.

3.3. Results of diatom analysis and radiocarbon dating

3.3.1. Takagi-Nemari valley bottom plain

The figures from Fig. 4 to Fig. 9 show the results of diatom analysis and radiocarbon dating at the sampling sites. Referring to the detailed description (Fujimoto 1990), this chapter presents the outline.

At Loc. Ne-1, the following four diatom zones were recognized (Fig. 4).

MI zone (below +0.4 m): This is a marine deposit indicating tidal flat environment.

FI zone (+0.4 ~ +0.6 m): This is a fresh-water deposit indicating fresh-water marsh environment.

MII zone (+0.6 ~ +1.3 m): This is a marine deposit indicating tidal flat environment. This zone is divided into two subzones further shown by MIIa and MIIb.

FII zone (above +1.3 m): This is a fresh-water deposit indicating fresh-water marsh or swamp environment. This zone is divided into two subzones further shown by FIIa and FIIb.

At Loc. Ne-2, three diatom zones correlated with FI, MII and FII at Loc. Ne-1

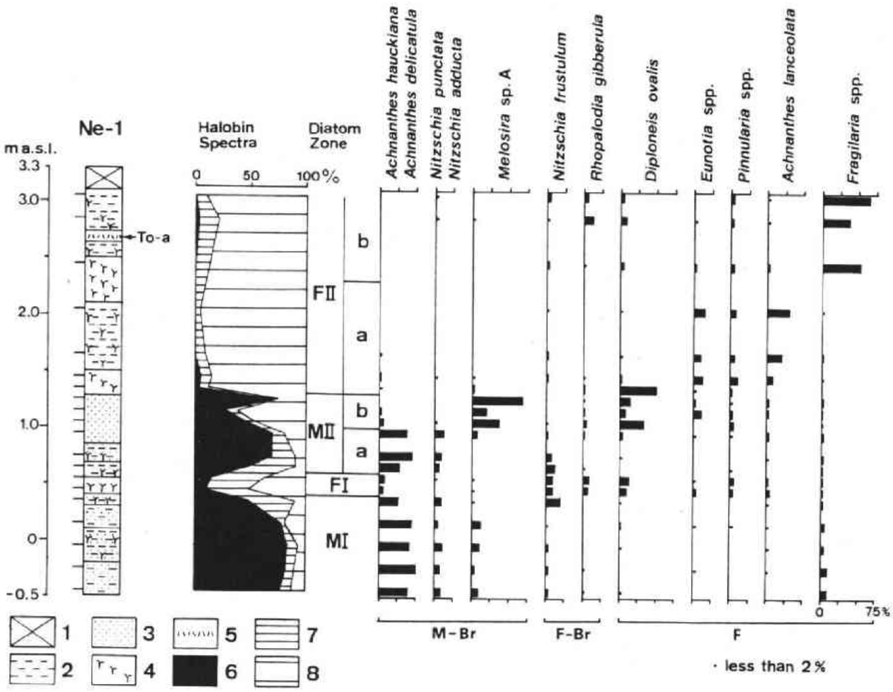


Fig. 4 Results of diatom analysis at Loc. Ne-1.
1. plowed soil, 2. silt, 3. sand, 4. humus, 5. tephra, 6. M-Br: marine-brackish water species, 7. F-Br: fresh-brackish water species, 8. F: fresh-water species.

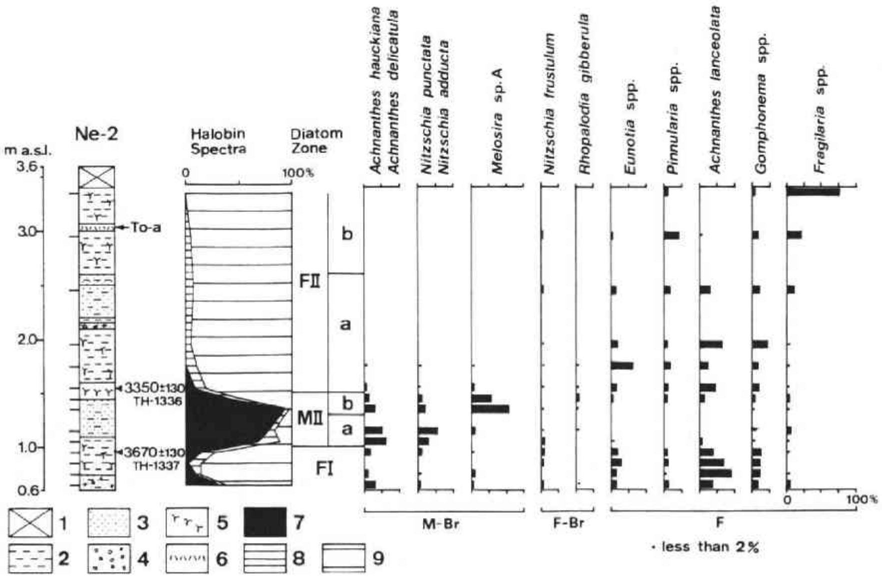


Fig. 5 Results of diatom analysis and radiocarbon dating at Loc. Ne-2.
1. plowed soil, 2. silt, 3. sand, 4. gravel, 5. humus, 6. tephra, 7. M-Br: marine-brackish water species, 8. F-Br: fresh-brackish water species, 9. F: fresh-water species.

were recognized (Fig. 5). Two radiocarbon ages were obtained from peaty silt accumulated on just upper and under horizons of MII zone.

At Loc. Ne-3, four diatom zones correlated with MI, FI, MII and FII were recognized (Fig. 6). However, the ratios of marine-brackish species in MI and MII zones are less than those of Loc. Ne-1 and Loc. Ne-2. The fact seems to indicate that this site is situated in the neighborhood of the terminal of the transgressions formed MI and MII zones. Four radiocarbon ages were obtained from this site.

At Loc. Ta-1, four diatom zones correlated with MI, FI, MII and FII were recognized (Fig. 7). However, the horizon correlated with FI doesn't indicate to be complete fresh-water deposit. The fact seems to indicate that this site is situated in the neighborhood of the terminal of the regression formed FI zone. Two radiocarbon ages were obtained from just upper and under horizons of MII zone.

At Loc. Ta-2, two diatom zones were recognized (Fig. 8). The marine deposit at this site is not divided into two zones (MI and MII zones), because the regression formed FI zone did not reached this site. The marine deposit at this site is named M zone. Two radiocarbon ages were obtained from this site. One is from just upper horizon of M zone, the other is from in M zone.

At Loc. Ta-3, all of the deposits were judged to be marine deposits from the results of FeS_2 contents analysis and diatom analysis. Three radiocarbon ages were

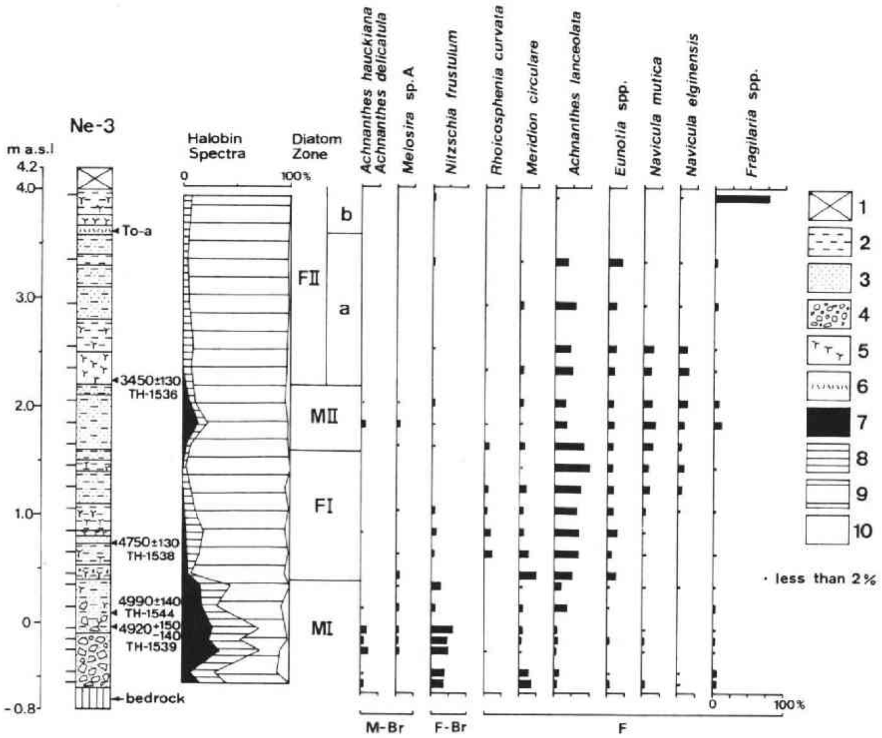


Fig. 6 Results of diatom analysis and radiocarbon dating at Loc. Ne-3.
1. plowed soil, 2. silt, 3. sand, 4. gravel, 5. humus, 6. tephra, 7. M-Br: marine-brackish water species, 8. F-Br: fresh-brackish water species, 9. F: fresh-water species, 10. unknown.

obtained from this site (Fig. 9).

3.3.2. Tedaru valley bottom plain

The figures from Fig. 10 to Fig. 13 indicate the results of diatom analysis and radiocarbon dating on the Tedaru valley bottom plain. The altitude of each sampling site is −0.6 m at Loc. Te-1, 0 m at Loc. Te-2, +0.2 m at Loc. Te-3 and +0.8 m at Loc. Te-4 respectively. This valley bottom plain was reclaimed about 350 years ago by construction of a dike.

At Loc. Te-1, all of the deposits consist of a series of marine deposit which is divided into three diatom subzones indicated as Te-Ma, Te-Mb and Te-Mc in order from the bottom (Fig. 10). Dominant species are, in Te-Ma subzone, *Cyclotella* sp. and *Cyclotella stylorum* which are marine planktonic species, in Te-Mb subzone, *Cocconeis scutellum* which is a brackish epiphytic species, and in Te-Mc subzone, *Nitzschia granulata* and *Nitzschia lanceolata* which are brackish benthic species. A radiocarbon

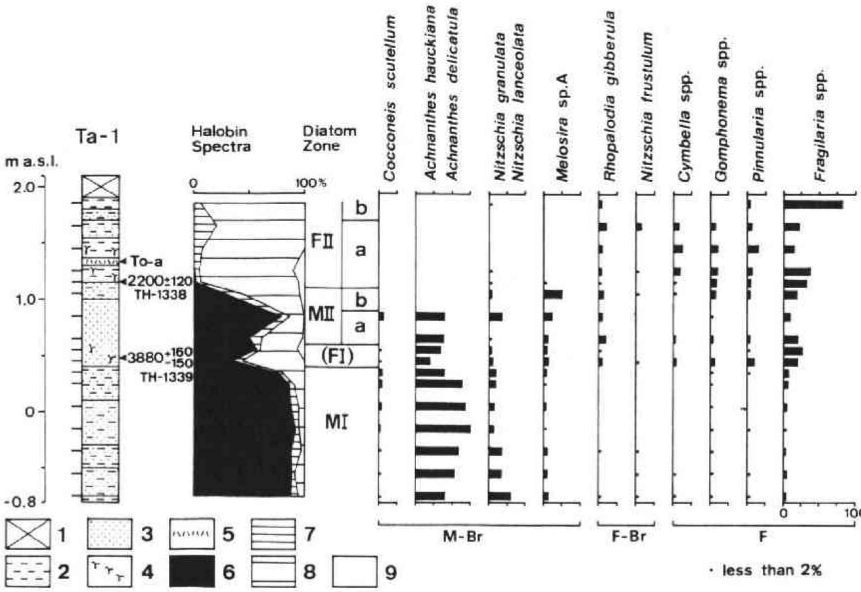


Fig. 7 Results of diatom analysis and radiocarbon dating at Loc. Ta-1.
1. plowed soil, 2. silt, 3. sand, 4. humus, 5. tephra, 6. M-Br: marine-brackish water spcies, 7. F-Br: fresh-brackish water species, 8. F: fresh-water species, 9. unknown.

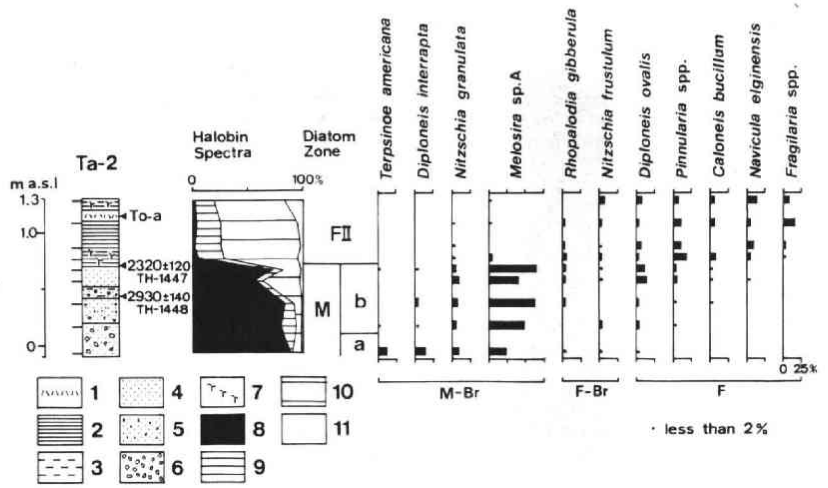


Fig. 8 Results of diatom analysis and radiocarbon dating at Loc. Ta-2.
1. tephra, 2. clay, 3. silt, 4. fine sand, 5. medium-coarse sand, 6. gravel, 7. humus, 8. M-Br: marine-brackish water species, 9. F-Br: fresh-brackish water species, 10. F: freshwater species, 11. unknown.

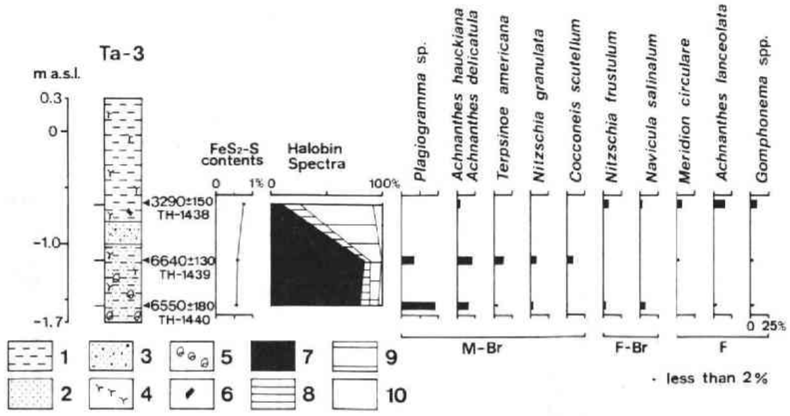


Fig. 9 Results of diatom analysis and radiocarbon dating at Loc. Ta-3.
1. silt, 2. fine sand, 3. medium-coarse sand, 4. humus, 5. shell fragment, 6. wood fragment, 7. M-Br: marine-brackish water species, 8. F-Br: fresh-brackish water species, 9. F: fresh-water species, 10. unknown.

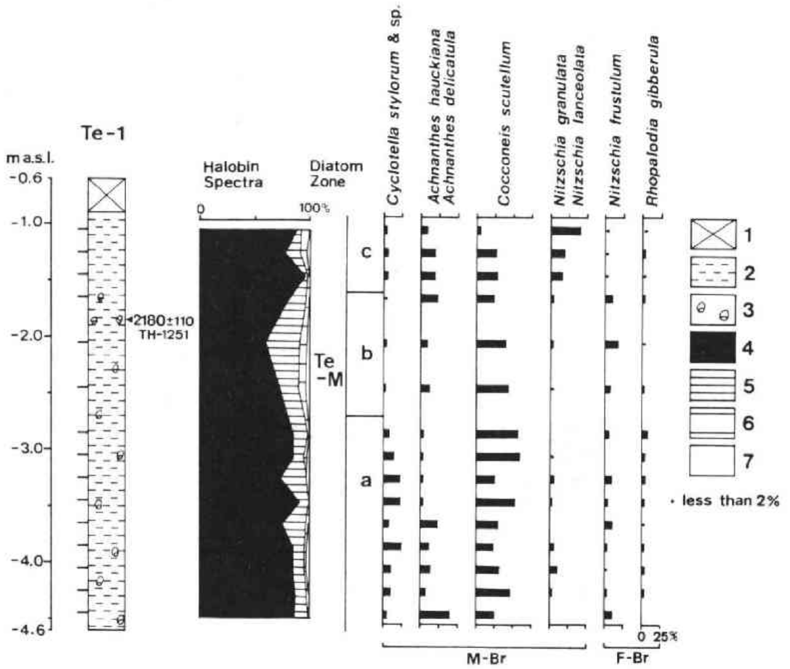


Fig. 10 Results of diatom analysis and radiocarbon dating at Loc. Te-1.
1. plowed soil, 2. silt, 3. shell fragment, 4. M-Br: marine-brackish water species, 5. F-Br: fresh-brackish water species, 6. F: fresh-water species, 7. unknown.

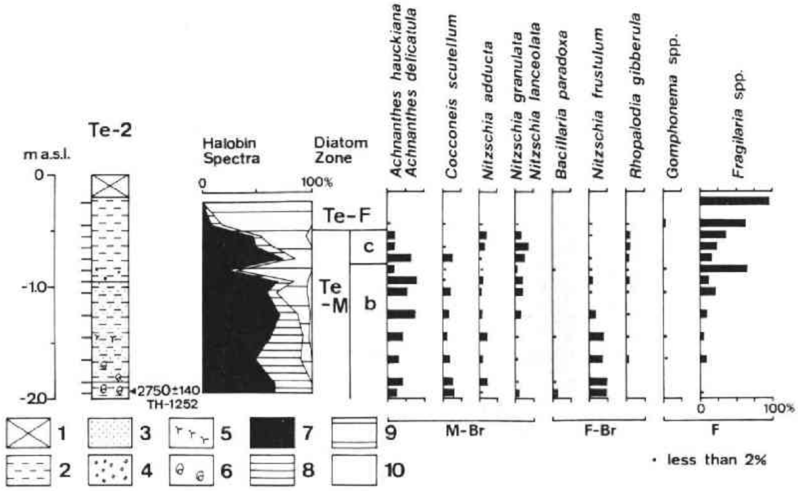


Fig. 11 Results of diatom analysis and radiocarbon dating at Loc. Te-2.
1. plowed soil, 2. silt, 3. sand, 4. gravel, 5. humus, 6. shell fragment, 7. M-Br: marine-brackish water species, 8. F-Br: fresh-brackish water species, 9. F: fresh-water species, 10. unknown.

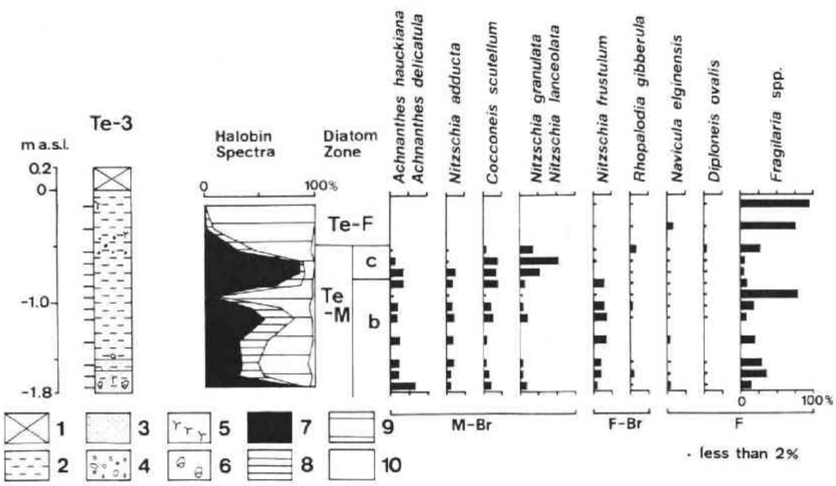


Fig. 12 Results of diatom analysis at Loc. Te-3.
1. plowed soil, 2. silt, 3. sand, 4. gravel, 5. humus, 6. shell fragment, 7. M-Br: marine-brackish water species, 8. F-Br: fresh-brackish water species, 9. F: fresh-water species, 10. unknown.

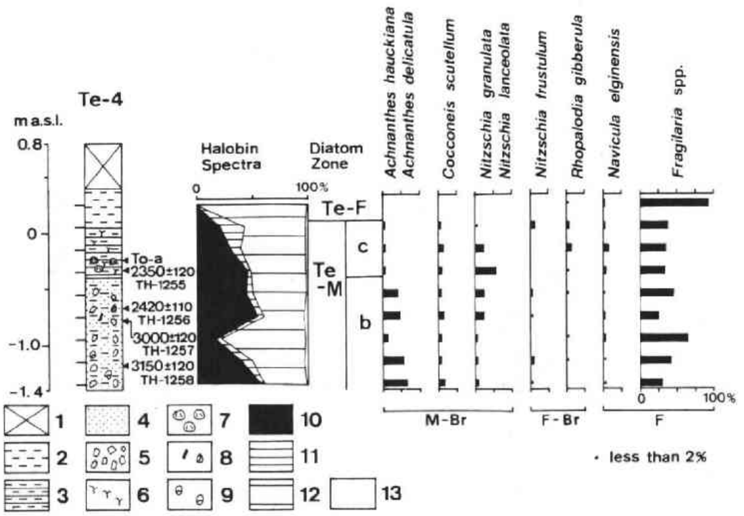


Fig. 13 Results of diatom analysis and radiocarbon dating at Loc. Te-4.
1. plowed soil, 2. silt, 3. silty clay, 4. sand, 5. gravel, 6. humus, 7. tephra, 8. wood fragment, 9. shell fragment, 10. M-Br: marine-brackish water species, 11. F-Br: fresh-brackish water species, 12. F: fresh-water species, 13. unknown.

date indicating 2,180±110 yr B.P. was obtained from shell fragments in the upper part of Te-Mb subzone.

At Loc. Te-2, marine deposit was recognized below −0.5 m. The marine deposit is divided into two subzones indicated as Te-Mb and Te-Mc. A radiocarbon age indicating 2,750±140 yr B.P. was obtained from shell fragments in Te-Mb subzone (Fig. 11).

At Loc. Te-3, the same diatom zones and subzones with Loc. Te-2 were recognized (Fig. 12).

At Loc. Te-4, the same diatom zones and subzones with Loc. Te-2 and Loc. Te-3 were recognized (Fig. 13). The fresh-water species in Te-M zone seems to be allochthonous one. Four radiocarbon ages were obtained from this site.

3.4. Late Holocene sea-level changes in Matsushima Bay

3.4.1. Successional reconstruction of the sea-level changes

The results of diatom analysis and radiocarbon dating on the Takagi-Nemari valley bottom plain (Fig. 4-Fig. 8) revealed two transgressions indicated as diatom zones MI and MII in the period between 5,000 yr B.P. and 2,200 yr. B.P. (Fig. 14). Carefull tracing of the boundary between marine deposits and fresh-water deposits made it possible to reconstruct successionally the following sea-level changes.

Sea level rose slowly until 4,800 yr B.P. The influence of the sea-level rise

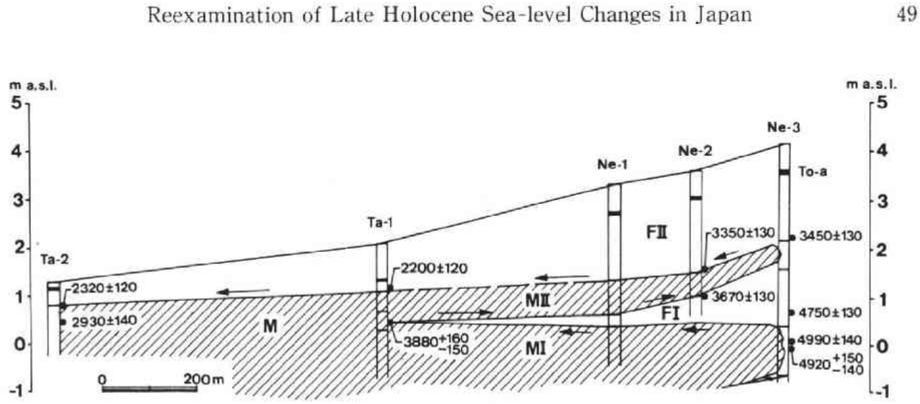


Fig. 14 Sedimentary structure shown by distribution of fossil diatom zone on the Takagi-Nemari valley bottom plain.
crosshatched area : showing marine deposite, arrous : showing course of shoreline migration.

reached to 0.4 m above the present sea level. Between 4,800 yr B.P. and 3,900 yr B.P., the sea level was stable ; after that time, it began to rise again. The influence of the later sea-level rise reached to about 2 m above the present sea level. After 3,500 yr B.P., the sea level began to fall. The upper limit of the tidal effect fell to +1.5 m at 3,350 yr B.P., and to +1.0 m at 2,200 yr B.P.

However, the mean tide level at each time is estimated to be 0.64 m below the boundary between marine deposits and fresh-water deposits, because the tidal range, which is 1.28 m at present, does not seem to have changed during late Holocene time, judging from the length of the bay during this period.

3.4.2. Regression during *Yayoi* period (around 2,000 yr B.P.)

The sea-level changes after 2,200 yr B.P. were not reconstructed successionally. However, the sea level around 2,000 yr B.P. was inferred by comparing the three diatom subzones in marine deposit clarified on the Tedaru valley bottom plain with the living diatom assemblages on the tidal flat and the bottom of the shallow sea. Though the existence of regression around 2,000 yr B.P. was presumed by several geomorphic evidences indirectly in Japan (Iseki 1974 *etc.*), it has not been confirmed by the deposit indicating the sea level at that time directly.

The samples of living diatoms were collected from 7 locations shown in Fig. 3. The dominant species of each sampling site are shown in Fig. 15. Loc. 1 and Loc. 2 situated in the under part of mid-tidal zone don't have notable dominant species, but *Nitzschia frustulum, Cocconeis scutellum* and *Achnanthes* sp. (*A. hauckiana* and *A. delicatula*) are found 10-15% respectively. Loc. 3 and Loc. 4 situated in low-tidal zone on the margin of inlet have almost the same assemblages with Loc. 1 and Loc. 2 except for a little increasing of *Cocconeis scutellum*. At Loc. 5 situated in low-tidal zone on

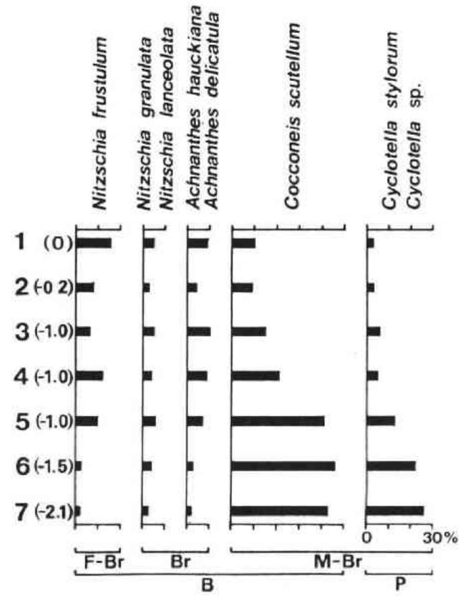


Fig. 15 Living diatom assemblages on tidal flat and shallow-sea bottom in front of the Tedaru valley bottom plain.
1～7 : sampling site number (Location is shown in Fig. 3), ( ) : altitude of sampling site (m), F-Br : fresh-brackish water species, Br : brackish water species, M-Br : marine-brackish water species, B : benthic species, P : planktonic species.

the center of inlet, and Loc. 6 and Loc. 7 situated in sub-tidal zone, *Cocconeis scutellum* and *Cyclotell* sp. are found notably.

The samples above mean tide level were not obtained, because the tidal flat above mean tide level doesn't exist in present coast of Matsushima Bay on account of construction of dikes along the coast. However, the facts which *Nitzschia granulata* and *Nitzschia lanceolata* are found dominantly in the upper part of the marine deposit at all of the fossile diatom sampling sites on the Tedaru valley bottom plain, and the assemblage is not found in the present environments under mean tide level enable to infer that the assemblage indicates an environment above mean tide level.

Table 1 shows the living diatom assemblages indicating respective environments and corresponding fossil diatom zones.

At Loc. Te-1, it is possible to infer that the horizon of -1.6 m became the environment between mean tide level and high-tidal zone after 2,200 yr B.P. on the basis of the existence of Te-Mc diatom subzone above -1.6 m and the result of radiocarbon dating (Fig. 10). Especially, it seems that the horizon between -1.6 m and -1.2 m deposited in the environment around mean tide level, because the contents of *Nitzschia granulata* and *Nitzschia lanceolata* are little relatively. The results of

Table 1 Living diatom assemblages indicating respective environments and corresponding fossil diatom zones.

<table>
<tr><th colspan="2">Tidal zone</th><th>Dominant species</th><th>Diatom zone</th></tr>
<tr><td colspan="2">High-tidal zone</td><td rowspan="2">Nitzschia granulata
Nitzschia lanceolata</td><td rowspan="2">Te-Mc</td></tr>
<tr><td colspan="2" rowspan="2">Mid-tidal zone</td></tr>
<tr><td rowspan="2">Nitzschia frustulum
Cocconeis scutellum
Achnanthes hauckiana & delicatula
(10～20% respectively)</td><td rowspan="2">Te-Mb</td></tr>
<tr><td rowspan="2">Low-tidal zone</td><td>Margin of inlet</td></tr>
<tr><td>Center of inlet</td><td rowspan="2">Cocconeis scutellum (40～50%)
Cyclotella stylorum & sp. (15～25%)</td><td rowspan="2">Te-Ma</td></tr>
<tr><td colspan="2">Sub-tidal zone</td></tr>
</table>

diatom analysis and radiocarbon dating at other sites on the Tedaru valley bottom plain support the inference mentioned above.

On the other hand, the regression occurred rapidly between Loc. Ta-2 and Loc. Ta-1 about 2,200 yr B.P. on the Takagi-Nemari valley bottom plain, though Loc. Ta-2 is situated at about 700 m seaward from Loc. Ta-1. The fact seems to indicate that the sea level fell rapidly about 2,200 yr B.P.

Judging from the data mentioned above, it is possible to infer that the regression during *Yayoi* period began about 2,200 yr B.P., and the sea level fell to c. 1.5 m below the present level.

3.4.3. The sea level around 6,500 yr B.P.

At Loc. Ta-3, numerous shell fossiles indicating the environment of the under part of tidal range and epiphytic marine-brackish diatoms are found in the horizon between −1.6 m and −1.5 m dated as 6,500±180 yr B.P., and numerous epiphytic marine-brackish diatom fossiles are found in the horizon between −1.2 m and −1.1 m dated as 6,640±130 yr B.P. (Fig. 9). The latter horizon doesn't contain shell fossiles and planktonic marine diatom fossiles. Judging from these facts, it is possible to infer that the sea level about 6,500 yr B.P. stood at about 1 m below the present one. The estimated level is several meter lower than that in most of previous studies in Japan.

Fig. 16 represents the reconstructed sea-level changes whose culmination age is 3,500 yr B.P.

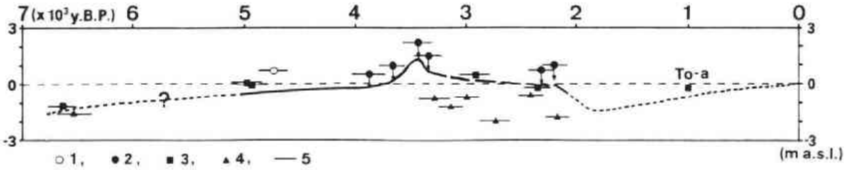


Fig. 16 Late Holocene sea-level changes curve in Matsushima Bay.
Solid line: reconstructed by tracing the course of shoreline migration strictly in time scale of 10^2 years. Broken line: reconstructed by using the additional data obtained from marine deposit. Dotted line: inferred by using other method.
[Radiocarbon age] 1. obtained from fresh water deposit. 2. obtained from the boundary between marine deposit and fresh water deposit. 3. obtained from high-tidal zone. 4. obtained from low-tidal zone. 5. range of measurement error ($\pm 1\sigma$).
To-a: Towada-a tephra (ca. 1,000 yr. B.P.).

4 Late Holocene sea-level changes in Nanao-nishi Bay

4.1. Outline of the study area

Nanao Bay is a small inner bay situated in the western part of Toyoma Bay, east coast of the Noto Peninsula, and is divided into three sea areas by Noto Island. The Hiyogawa valley bottom plain, a study area, faces Nanao-nishi Bay located in the innermost part of Nanao Bay (Fig. 17). No bars and beach ridges are formed along the coastline of Nanao-nishi Bay, because wave action and coastal currents are too

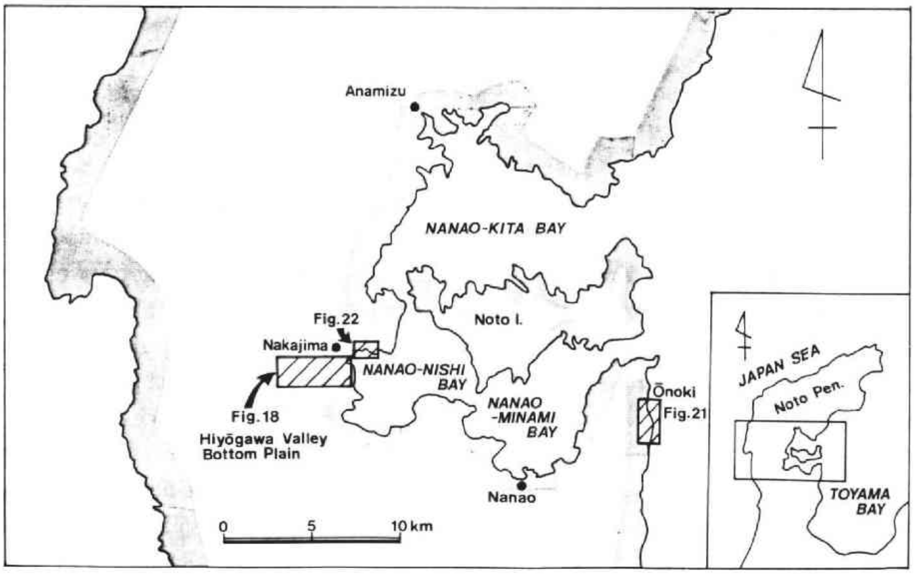


Fig. 17 Map showing the study areas on the Noto Peninsula.

weak to form them. Tidal range in spring tide is only about 40 cm.

The Noto Peninsula is considered to be an upheaval area, because it is fringed by Pleistocene and Holocene marine terraces. However, the uplift rate of Nanao-nishi Bay area inferred from the altitude of the marine terraces is relatively small in the Noto Peninsula (Ota and Hirakawa 1979, *etc.*). Moreover, no active faults are found across the Hiyogawa valley bottom plain.

4.2. Study method

FeS_2 contents analysis was applied for the recongition of the boundary between marine deposit and fresh-water deposit, because diatoms were not found in the Holocene deposits of the valley bottom plain. The method of the analysis followed Shiragami (1985). The results of the analysis were presented by the ratio of the sulfur weight to the sample weight (FeS_2-S contents) like Nakai *et al.* (1982) and Shiragami (1985).

The samples for the analysis were collected from 6 locations (Loc. 1 ~ Loc. 6) indicated in Fig. 18. The samples for radiocarbon dating were mainly taken from the boundary between marine deposit and fresh-water deposit.

The altitudes of sampling sites were determined by leveling from sea surface by autolevel.

4.3. Results of FeS_2-S contents analysis and radiocarbon dating

Fig. 19 shows the geologic columns of sampling sites and the results of FeS_2-S contents analysis and radiocarbon dating. The interval between sampling sites except for that between Loc. 6 and Loc. 7 are represented in proportion to the real interval. The detail of the results of the analysis and dating will be presented by the other paper

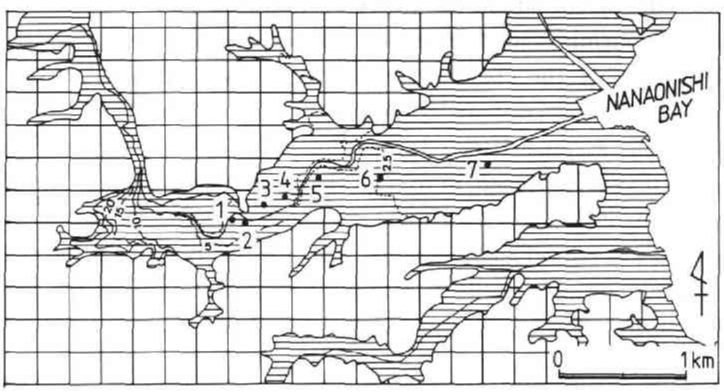


Fig. 18 Map showing the locations of the sampling sites on the Hiyogawa valley bottom plain.

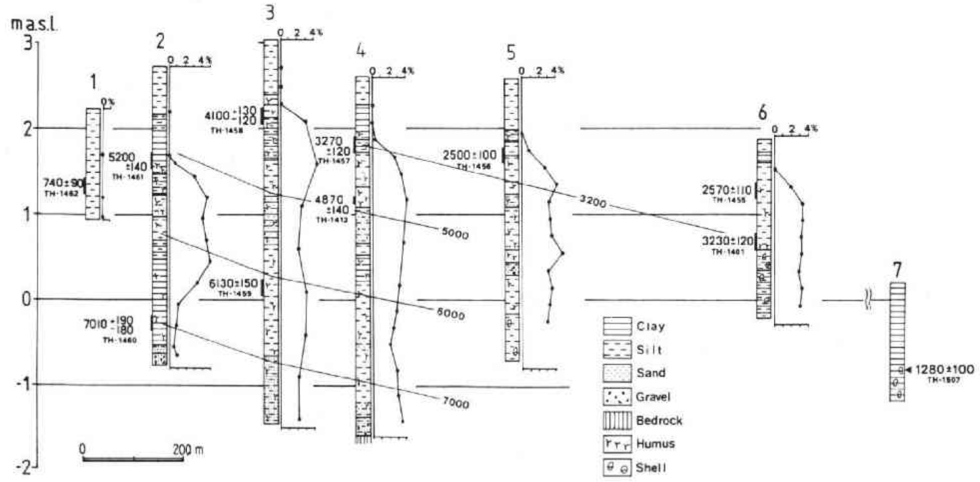


Fig. 19 Geologic columns of the sampling sites and the results of FeS_2-S contents analysis and radiocarbon dating.

(Fujimoto, in press).

The sediments containing sulfur which indicate marine environment were recognized at all of the sites except Loc. 1. The altitude of the upper limit of the marine deposit in each site is +1.7 m at Loc. 2, +2.1 ~ +2.3 m at Loc. 3, +1.8 m at Loc. 4, +1.7 m at Loc. 5, and +1.3 ~ +1.5 m at Loc. 6 respectively. At Loc. 2, the altitude of the under limit of the marine deposit which is −0.1 m has been recognized too.

Eleven radiocarbon ages shown in Fig. 19 were obtained from the valley bottom plain. Samples for dating are almost organic silt or clay except for TH-1507 of Loc. 7 whose sample is shell. The age obtained from the under limit of marine deposit at Loc. 2 indicates the oldest one in the valley bottom plain, and the ages obtained from the upper limit of marine deposit line up in order of old age from landward to seaward. The facts indicate that the coastline has advanced gradually after the Postglacial transgression.

At Loc. 1, sulfur was not detected from any of horizon, and the youngest age in the valley bottom plain was obtained, in spite of the innermost location. Judging from the facts, the sediment of this site seems to bury shallow valley formed by river erosion. It is inferred that the buried shallow valley was formed between 2,400 yr B.P. and 740 yr B.P. From the period of vally burying, it is correlative with the buried shallow valley formed during *Yayoi* period as indicated by Iseki (1974), *etc*.

4.4. Reconstruction of the relative sea-level changes

Fig. 20 indicates the relative sea-level changes curve depicted from the results of

FeS_2-S contents analysis and radiocarbon dating. The curve was represented by broken line and dotted line, because the course of shoreline migration wasn't always traced continuously on account of the existence of the time intervals of 700 to 1,600 years between the adjoining ages obtained from the boundary between marine deposit and fresh-water deposit (Fig. 19). However, it is hard to consider that the sea-level rise which increased the depth of water occurred rapidly during the time intervals, because the marine deposit in the valley bottom plain seems to have deposited in the depth of water where halophytic vegetation could have grown, judging from the existence of much organic materials in the deposit.

The sedimentation rate of marine deposit at Loc. 4, which is 0.41 mm/yr, calculated by the use of two radiocarbon ages, is less than half of those at other sites, which are 1.05 mm/yr at Loc. 2, 0.99 mm/yr at Loc. 3, and 0.91 mm/yr at Loc. 5 respectively. The radiocarbon ages seem to indicate the correct depositional ages, because the geomorphic sufaces at 3,200 yr B.P., 5,000 yr B.P., 6,000 yr B.P., and 7,000 yr B.P. reconstructed from the radiocarbon ages are represented by almost parallel line (Fig. 19). Therefore, it is thinkable that the slow sedimentation rate at Loc. 4 is caused by a diastem between the dating horizons. The diastem seems to have formed by relative sea-level down between 4,000 yr B.P. and 3,300 yr B.P. It is inferred from the difference between the original sedimentation rate and observed one that the sea level fell 0.9 m at least. The relative sea-level fall is represented in Fig. 20, too.

4.5. Elimination of the influences of crustal movement

It is possible to infer the history of uplift in Nanao-nishi Bay area by using the data obtained from Onoki area (Fig. 17, 21). Trace fossils of boring shells are found at two different levels on rock cliff at Onoki (Fig. 21-B, C). The fact indicates that two intermittent uplift events subsequent to earthquakes took place. The periods of the events are inferred as follows.

Shell fossils in the sand and gravel layer continuing the upper trace fossils of

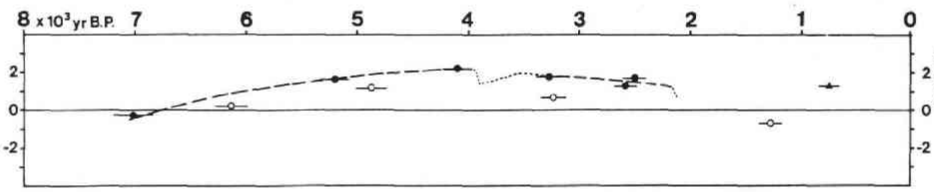


Fig. 20 Late Holocene relative sea-level changes curve in Nanao-nishi Bay.
[Radiocarbon age] 1. obtained from the boundary between marine deposit and fresh-water deposit. 2. obtained from marine deposit. 3. obtained from fresh-water deposit. Measurement error: $\pm 1\sigma$.

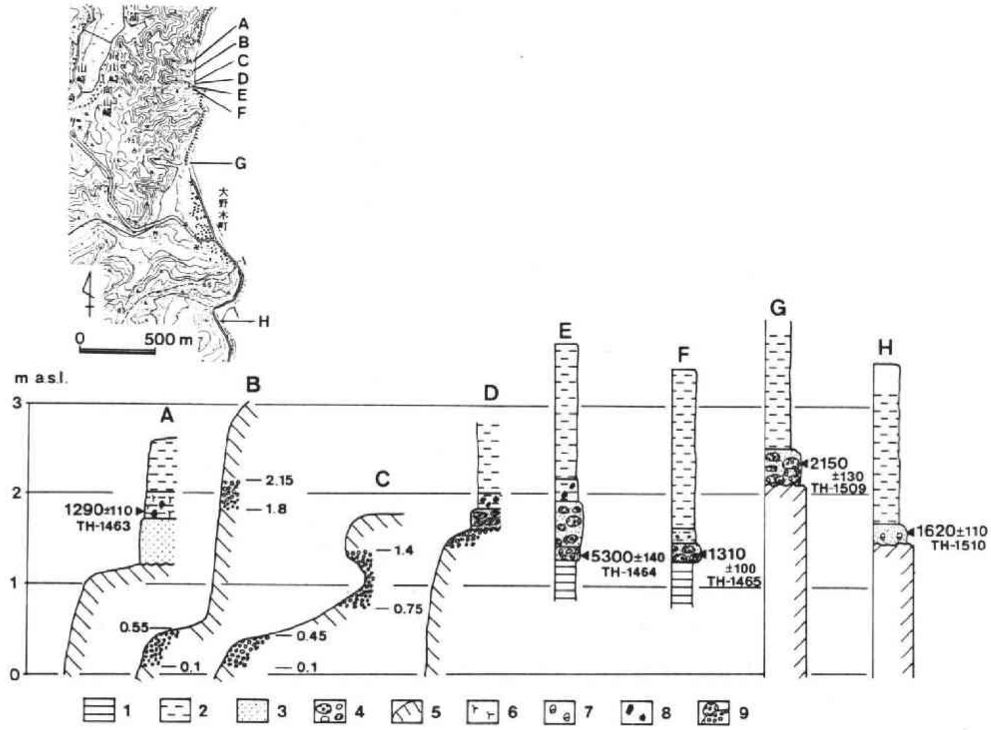
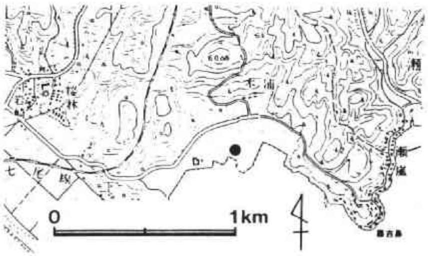


Fig. 21. Several geomorphic evidences of uplift and emerged shell fossils at Onoki. 1. clay, 2. silt, 3. sand, 4. gravel, 5. bedrock (Miocene mudstone), 6. humus, 7. shell fragments, 8. earthenware fragments (early *Kofun* period : A.D. 4～5C), 9. trace fossils of boring shell.

boring shells on rock cliff indicate from 5,300 yr B.P. (Loc. E) to 2,150 yr B.P. (Loc. G). The silt layer including earthenware fragments of early *Kofun* period (A.D. 4～5C) overlies the sand and gravel layer (Loc. D, E). The shell fragments dated as ca. 1,600 yr B.P. in the sand layer at Loc. H doesn't seem to be marine deposit but to be backshore deposit moved by wave action, because all of them consist of defaced small fragments. These facts indicate that the upper trace fossils of boring shells emerged between ca. 2,200 yr B.P. and ca. 1,600 yr B.P., and the lower emerged after 1,600 yr B.P. The charcoals dated as 1,310 yr B.P. in the sand and gravel layer at Loc. F seem to be contaminated by younger carbon derived from the upper layer.

On the other hand, in Nanao-nishi Bay area, the Holocene marine terraces are found at two levels. Judging from their levels, the terraces seem to be correlative with the two-level trace fossils of boring shells at Onoki, respectively. Moreover, the altitudes of paleoshoreline in the time between ca. 5,200 yr B.P. and ca. 2,400 yr B.P. in the Hiyogawa valley bottom plain nearly agree with the altitudes of the upper trace



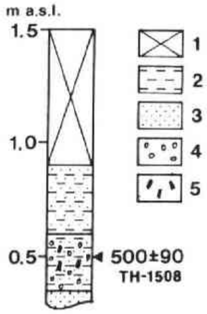


Fig. 22 Holocene marine terrace deposits in Nanao-nishi Bay and a radiocarbon age obtained from the deposit.
1. plowed soil, 2. silt, 3. sand, 4. gravel, 5. charcoal.

fossils of boling shells at Onoki. Therefore, it is quite probable that two intermittent uplift events occurred after 2,200 yr B.P. in Nanao-nishi Bay area, like the Onoki area. The latter uplift event is considered to have provided emergence of the lower trace fossils of boring shells and formation of the lower terraces between 1,600 yr B.P. and 500 yr B.P., because radiocarbon age dated as 500 yr B.P. was obtained from the lower terrace deposit (Fig. 22). Moreover, the possibility that the relative sea-level fall between 4,000 yr B.P. and 3,000 yr B.P. found in the deposit of the Hiyogawa valley bottom plain was caused by intermittent uplift event like the events after 2,200 yr B.P. can be pointed out. Displacement in each event is estimated as follows on the basis of the average occurrence interval of the events, the average uplift rate inferred from the height of the Last Interglacial marine terraces, and the empirical rule that displacement in each earthquake lies between a half and double of the average displacement.

The three intermittent uplift events are named event 1 to event 3 in order from new event respectively. The maximum of the average occurrence interval of earthquake inferred from the occurrence interval of the events is estimated at 1,750 years by supposing that event 1 and event 3 occurred in 500 yr B.P. and 4,000 yr B.P. respectively. The minimum of it is estimated at 1,100 years by supposing that event

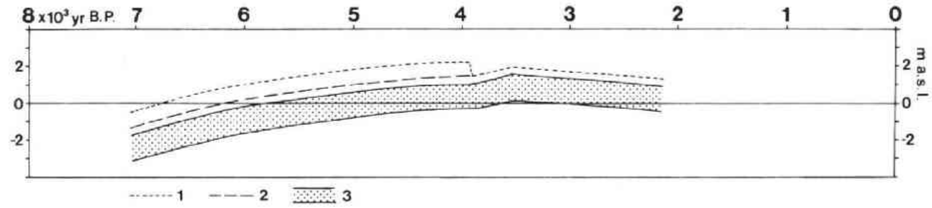


Fig. 23 Late Holocene sea-level changes curve eliminated the influences of uplift. 1. relative sea-level changes curve, 2. sea-level changes curve eliminated the displacement in event 3, 3. sea-level changes curve eliminated the displacements in event 1, event 2 and event 3.

3 occurred in 3,300 yr B.P. and that present is in a situation immediately before the next event. The average uplift rate during late Pleistocene time is estimated at 0.25 mm/yr from the altitude of the Last Interglacial marine terraces around the Hiyogawa valley bottom plain, which is 30 m, by supposing that the peak of sea level during Last Interglacial occured in 120,000 yr B.P. and stood at the same level as the present one. Terefore, the maximum displacement following an earthquake is calculated at between $1{,}750 \times 0.25 \times 2 = 875$(mm) and $1{,}100 \times 0.25 \times 2 = 550$(mm), and the minimum one is calculated at between $1{,}750 \times 0.25 \times 1/2 = 219$(mm) and $1{,}100 \times 0.25 \times 1/2 = 138$(mm). It is quite possible that the average occurrence interval of earthquake is about 1,750 years, because the displacement following event 3 is almost equal to the maximum one in the case that it was estimated at 1,750 years. Therefore, the displacement following an earthquake in Nanao-nishi Bay area is estimated at between 0.2 m and 0.9 m, and the total displacement caused by event 1 and event 2 is estimated at between 0.4 m and 1.8 m.

Elimination of the influence of the uplift estimated as above leads to reconstruction of the late Holocene sea-level changes shown in Fig. 23. This curve indicates that the highest sea level during Holocene time occurred in about 3,500 yr B.P. like the Matsushima Bay's one.

5 Late Holocene sea-level changes in Oku-Tokyo Bay

5.1. Outline of the study area

The alluvial plain facing Tokyo Bay is divided into two major lowlands by Omiya Upland (Fig. 24). They are called the Arakawa Lowland and the Nakagawa Lowland. The Postglacial transgression reached about 125 km and 145 km inland from the mouth of Tokyo Bay along the Arakawa Lowland and the Nakagawa Lowland, respectively (Endo *et al.* 1982, *etc.*).

In a present bay penetrated far into the land, the tidal range in the bay bottom is

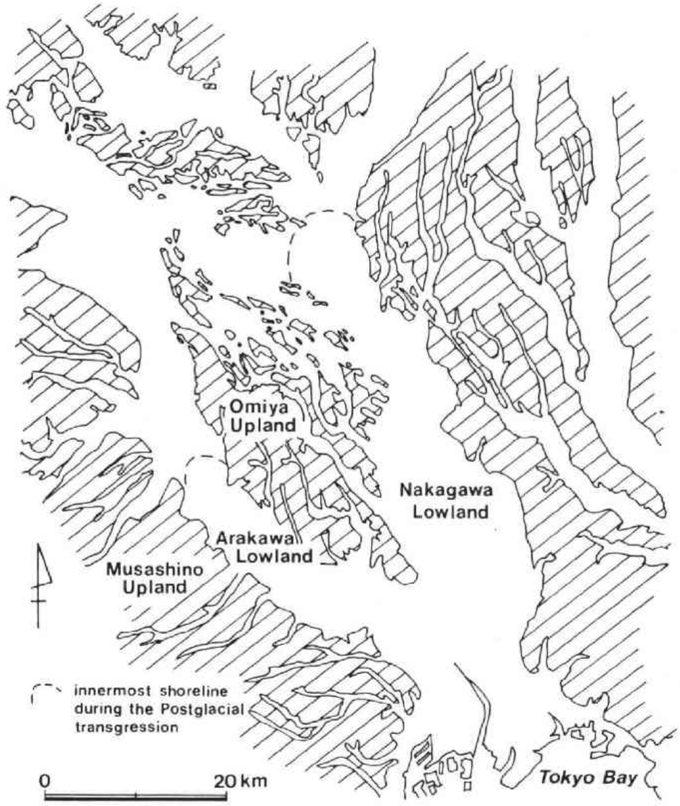


Fig. 24 Distribution of alluvial plains in the Kanto Plain.

larger than that at the mouth. For example, in Tokyo Bay, the tidal range at the mouth is 159 cm, but it is amplified to 205 cm at Harumi situated in the bay bottom. In the Bay of Fundy in Canada, which has the bay axis of over 300 km in length, the tidal range is amplified to more than 15 m at the bay head (Redfield 1950, *etc.*). Therefore, it is possible that the tidal range in Oku-Tokyo Bay was amplified considerably than that in present Tokyo Bay.

Oku-Tokyo Bay area may have been affected by the Kanto basin forming movement which has provided the Kanto Plain the two centers of subsidence, *i.e.*, the northern part of Tokyo Bay and the northern part of the Nakagawa Lowland, since late Pleistocene age (Kodama *et al.* 1981, *etc.*).

5.2. The equations explaining the tidal phenomenon in a bay

It is inferred that the upper limit of marine deposit determined by diatom analysis indicates the sedimentary environment of around spring high tide level (Fujimoto and

Ando 1990). Therefore, the tidal range at any time and place in the paleobay has to be reconstructed for the inferrence of the paleosealevel.

The tide in a bay may be considered to be due to two progressive waves traveling in opposite directions. One of these is the primary wave invaded from the open sea. The other is the reflected wave produced at the bay head which is a barrier. At the barrier, the two waves are equal in elevation and phase. If the waves don't undergo frictional damping, a standing wave is formed by overlapping of these waves. However, a little difference in time of tide is observed actually in a bay between the bay mouth and the bay head. This indicates the existence of the effect of the damping. The equations explaining the change of water level in a bay dut to tide, which is considered the effect of the damping, are presented by Redfield (1950) as follows.

In a uniform channel, the elevation of the primary wave is give by:

$$\eta_1 = A\cos(\sigma t - kx)e^{-\mu x} \tag{1}$$

that of the reflected wave by:

$$\eta_2 = A\cos(\sigma t + kx)e^{\mu x} \tag{2}$$

where A is the amplitude of each of the wave at the bay head, σ is the angular frequency ($=2\pi/T$, where T is the period. In this paper, the period of the principal lunar semidiurnal tide M_2 which has the largest tide generating force is used.); t is the time measured from the time of high water at the bay head, when $t=0$, k is the wave number, x is the distance measured from the bay head, where $x=0$, and μ is the damping coefficient. The wave number is given by:

$$k^2 = k_0^2 + \mu^2 \tag{3}$$

where k_0 is the wave number in case of no effect of damping given by $k_0 = 2\pi/L$, where L is the wave length ($=(gh)^{1/2}T$, where g is the gravitational acceleration, and h is the mean depth of the bay). From (1) and (2), the elevation of the water, η, at any time and place along the channel is given by:

$$\begin{aligned}\eta &= \eta_1 + \eta_2 \\ &= A\{\cos(\sigma t - kx)e^{-\mu x} + \cos(\sigma t + kx)e^{\mu x}\}.\end{aligned} \tag{4}$$

High water occurs when $\delta\eta/\delta t = 0$. Hence, the local time angle of high water, σt_H, is denoted by:

$$\sigma t_H = \tan^{-1}\{-\tan(kx)\cdot\tanh(\mu x)\}. \tag{5}$$

Moreover, the ratio of the tidal range at any place, η_x, to that at the innermost, $\eta_{x=0}$, is given by:

$$\eta_x/\eta_{x=0} = [\{\cosh(2\mu x) + \cos(2kx)\}/2]^{1/2} \tag{6}$$

Therefore, in a bay which has its length l, the ratio, R, of the tidal range at any place to that at the mouth, $\eta_{x=-l}$, is given by :

$$R=\eta_x/\eta_{x=-l}$$
$$=[\{\cosh(2\mu x)+\cos(2kx)\}/\{\cosh(2\mu l)+\cos(2kl)\}]^{1/2}. \qquad (7)$$

5.3. Method for estimation of the tidal ranges during the Postglacial transgression

For the estimation of the tidal ranges during the Postglacial transgression, it is necessary to know the length of bay axis, the mean depth of water of the bay, and the damping coefficient of tidal wave in the bay. It is possible to estimate the length of bay axis at any time by inferring the position of shoreline from the age of marine deposit at its upper limit. However, it is difficult to estimate the mean depth of water and the damping coefficient at any time, because the submarine topography at any time during the Postglacial transgression is hardly reconstructed owing to shortage of radiocarbon dates. Then, the present mean depth, 20 m, was used for the calculation, and the damping coefficient was indirectly presumed from the present damping coefficients in Tokyo Bay, Ariake-kai Bay, and Ise Bay, which were calculated from the observed tidal data as follows.

The tidal data in Tokyo Bay were obtained from four sites, those are Yokosuka, Yokohama, Kawasaki, and Harumi (Fig. 25). The differences in time of tide between each site and the mouth of the bay, Mera, are shown in Table 2 by the mean difference in time of tide of every high tide from January to June, 1990. The difference in time

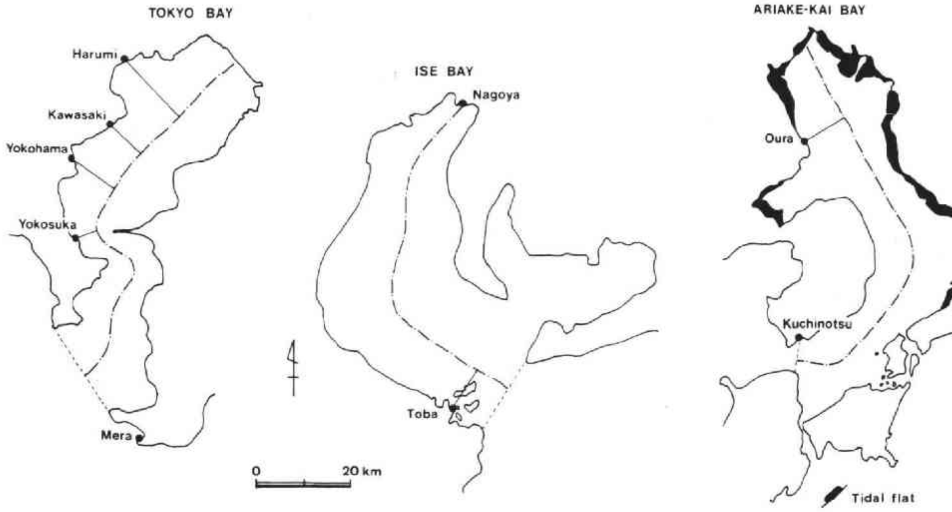


Fig. 25 Features of Tokyo Bay, Ise Bay, and Ariake-kai Bay.

Table 2 Difference in time of tide from the mouth of Tokyo Bay

	Distance from bayhead (km)	Distance from baymouth (km)	Difference in time of tide from baymouth (min.)
Yokosuka	47	37	20.0
Yokohama	38	46	20.7
Kawasaki	27	57	21.5
Harumi	16	68	23.0

Table 3 Damping coefficients of tidal wave in some bays of Japan

	Length of bay (km)	Mean depth of bay (m)	Difference in time of tide (min.) (bayhead side-baymouth side)	Damping coefficient
Tokyo Bay	84	20	20.0 (Yokosuka-Mera)	2.36×10^{-3}
			3.0 (Harumi-Yokosuka)	1.17×10^{-3}
Ariake-Kai Bay	86	20	15.5 (Oura-Kuchinotsu)	1.33×10^{-3}
Ise Bay	78	20	−1.5 (Nagoya-Toba)	—

of tide between Mera and Harumi, 68 km inside from Mera, is 23 minutes. On the other hand, that between Mera and Yokosuka situated 31 km inside from Mera is 20 minutes. The facts indicate that the damping coefficient in Tokyo Bay may not be explained by one certain value. The damping coefficient between Yokosuka and Harumi calculated from Equation (5) is 1.17×10^{-3}, and that between Yokosuka and Mera is 2.36×10^{-3}. However, the former is too small for the damping coefficient of Tokyo Bay, because the difference in time of tide between the mouth of the bay and Yokosuka calculated by using it, which is 9.8 minutes, is smaller than the observed one. Moreover, the latter is too large, because the difference in time of tide between Yokosuka and Harumi calculated by using it, which is 6.2 minutes, is larger than the observed one. It is hence estimated that the present damping coefficient of Tokyo Bay is between 1.17×10^{-3} and 2.36×10^{-3}. On the other hand, the damping coefficient of Ariake-kai Bay, where the tidal range reaches over 5 m, is estimated as 1.33×10^{-3} from Equation (5) by using the difference in time of tide between Oura and Kuchinotsu (Fig. 25, Table 3). In Ise Bay, the difference in time of tide is not found between the bay mouth and the bay head (Table 3), namely, the effect of damping is not recognized. It seems that the reasons why the effect of damping is not recognized in Ise Bay are that the bay is relatively wide, especially at the mouth, and the degree of bending of the bay is relatively small (Fig. 25).

Oku-Tokyo Bay had no bottleneck except for its mouth and ran almost straightly

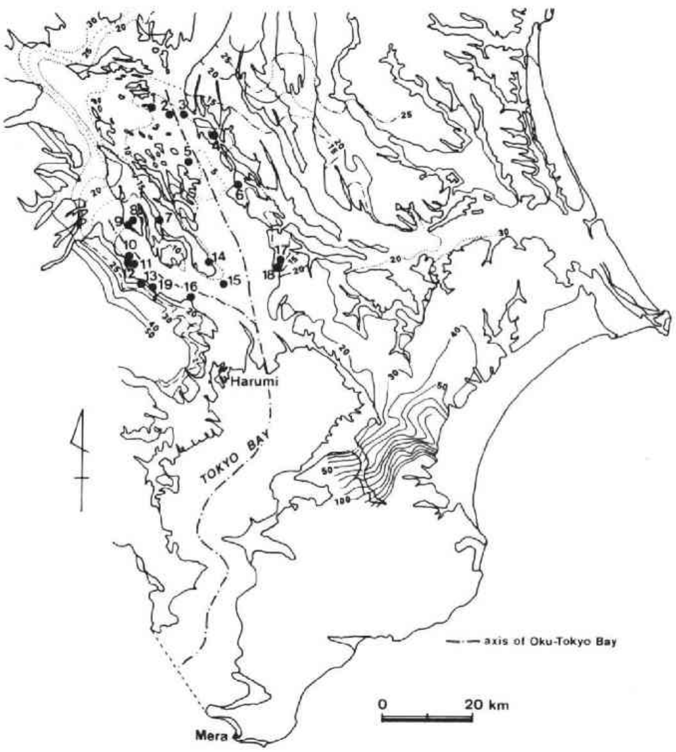


Fig. 26 Map showing the locations quoted the data concerned with the upper limit of marine deposit for calculation of amplification rate of tidal range.
Contour lines indicate the altitude of the top of the Joso clay correlated with the Shimosueyoshi Formation deposited in late Pleistocene (after Kodama *et al.* 1981).

in the longer branch bay which correspond to the present Nakagawa Lowland (Fig. 26). Hence, the damping coefficient in Oku-Tokyo Bay seems not so different from that in present Tokyo Bay. The minimum and maximum of the damping coefficient in the present Tokyo Bay, which are 1.17×10^{-3} and 2.36×10^{-3} respectively, are thus applicable to the estimation of tidal ranges during the Postglacial transgression.

The tidal ranges during the Postglacial transgression are estimated from the amplification ratio of tidal range obtained from Equation (7) for the emerged time of nineteen sites shown in Fig. 26. The present tidal range of spring tide at Mera, 159 cm, was used for the calculation on the assumption that the tidal range at the mouth of the bay has not changed during late Holocene time.

5.4. Recognition of paleosealevels and reconstruction of relative sea-level changes

The altitudes of the upper limit of marine deposits, the amplified tidal ranges, and

Table 4 The altitudes of the upper limit of marine deposits and the sea-levels after revision of the tidal ranges in Oku-Tokyo Bay

Loc. No.	Altitude of top of marine deposit (m)	Age (yr B.P.)	Length of bay (km)	Distance from bay head (km)	$\mu=1.17\times10^{-3}$ Amplification ratio	$\mu=1.17\times10^{-3}$ Tidal range (m)	$\mu=1.17\times10^{-3}$ Mean sea level (m)	$\mu=2.36\times10^{-3}$ Amplification ratio	$\mu=2.36\times10^{-3}$ Tidal range (m)	$\mu=2.36\times10^{-3}$ Mean sea-level (m)	References
1	0.7	4,800	137	0	4.10	651	−2.6	2.75	437	−1.5	Hirai (1983)
2	1.0	4,800~4,100	135	0	3.88	617	−2.1	2.71	431	−1.2	Sakaguchi (1986)
3	0.6	4,800~4,100	134	0	3.78	600	−2.4	2.69	428	−1.5	Hirai (1983)
4	2.5	—	145~127	18~0	4.94~3.14	785~499	−1.4~0	2.76~2.51	439~399	+0.3~+0.5	Wajima *et al.* (1968)
5	−0.7	4,100	122	0	2.78	442	−2.9	2.36	375	−2.6	Sakaguchi (1968)
6	3.5	5,000	140	25	4.31	685	+0.1	2.70	429	+1.4	Sakaguchi and Kashima (1986)
7	2.95	5,000	140	26	4.30	683	−0.5	2.69	428	+0.8	Ando (1982)
8	1.6	6,500	144	22*	4.79	762	−2.2	2.74	436	−0.6	Ando and Fujimoto (1990)
9	2.3	5,500	142	20*	4.59	730	−1.3	2.74	436	+0.1	*ibid.*
10	3.3	6,000	143	26*	4.64	737	−0.4	2.71	431	+1.1	Fujimoto and Ando (1990)
11	2.9	5,500	142	27*	4.51	717	−0.7	2.70	429	+0.8	*ibid.*
12	3.25	6,000~5,500	143	27*	4.62	735	−0.4	2.70	429	+1.1	Hasegawa (1967)
13	3.3	6,900	145	34*	4.73	752	−0.5	2.64	420	+1.2	Fujimoto and Ando (1990)
14	3	6,500	144	43	4.46	709	−0.5	2.55	405	+1.0	Kosugi (1987)
15	3	5,500	142	45	4.21	669	−0.3	2.52	401	+1.0	Endo *et al.* (1987)
16	2.2	4,800~4,050	137~122	38*~22*	3.81~2.71	606~431	−0.8~0	2.55~2.31	405~367	+0.2~+0.4	Ando (1988)
	1.6	3,050~2,100	122~101	22*~0	2.71~1.81	431~288	−0.6~+0.2	2.31~1.75	367~278	−0.2~+0.2	
17	3	3,500	122~97	25~0	2.69~1.76	428~280	+0.9~+1.6	2.29~1.71	364~272	+1.2~+1.6	Endo *et al.* (1989)
18	2.1	<3,500	122~97	25~0	2.69~1.76	428~280	0~+0.7	2.29~1.71	364~272	+0.3~+0.7	*ibid.*
19	2.6	2,900(?)	110	0	2.17	345	+0.9	2.01	320	+1.0	Fujimoto and Ando (1990)

* In the case of locations in the Arakawa Lowland, the distance arranged to one measured on the axis of the paleobay in the present Nakagawa Lowland.

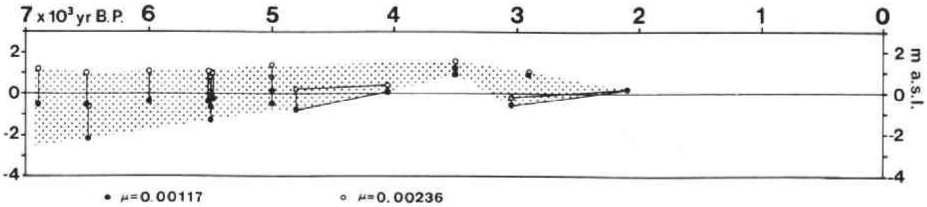


Fig. 27 Late Holocene sea-level changes curve after revision of the tidal range in Oku-Tokyo Bay.

the paleosealevels after revising the tidal ranges in Oku-Tokyo Bay are shown in Table 4. In case of $\mu=1.17\times10^{-3}$, the tidal ranges in the bay bottom during the peak of the Postglacial transgression are estimated at more than 7 m. In case of $\mu=2.36\times10^{-3}$, they are estimated at more than 4 m. Therefore, the sea levels during the Postglacial transgression have to be recognized at fairly lower levels than the upper limit levels of marine deposits as indicated in Table 4.

The regional differences in the revised paleosealevels at the same time seem to reflect the regional characteristics of crustal movement. For example, the paleosealevels around 6,000 yr B.P. are recognized at relatively lower level at Loc. 8 and Loc. 9 situated on the valley bottom plain in the western part of the Omiya Upland, on the other hand, those of Loc. 10～Loc. 13 situated on the Musashino Upland side, and Loc. 14 and Loc. 15 situated on the south side of the Omiya Upland are recognized at relatively higher level. Those of around 4,500 yr B.P. are recognized at relatively lower level at Loc. 1～Loc. 3 and Loc. 5 situated on the northern part of the Nakagawa Lowland, on the other hand, those of Loc. 6, Loc. 7 and Loc. 16 situated on the other areas are recognized at relatively higher level (Table 4). A part of the regional differences mentioned above may reflect the effect of the Kanto basin forming movement, because the regional trend partially accords with the trend of the Kanto basin forming movement indicated by Kodama *et al.* (1981), and so on (Fig. 26).

Fig. 27 shows the late Holocene sea-level changes in Oku-Tokyo Bay reconstructed from the revised sea levels shown in Table 4. The revised sea levels between 6,900 yr B.P. and 5,500 yr B.P. are recognized at between -2.2 m and -0.3 m in case of $\mu=1.17\times10^{-3}$, and at between -0.6 m and $+1.1$ m in case of $\mu=2.36\times10^{-3}$ (Loc. 8～Loc. 15). On the other hand, the revised sea levels at 3,500 yr B.P. are recognized at between $+0.9$ m and $+1.6$ m in case of $\mu=1.17\times10^{-3}$, and at between $+1.2$ m and $+1.6$ m in case of $\mu=2.36\times10^{-3}$ (Loc. 17). Loc. 17 is situated in the area where the relative uplift rate seems to be small in Oku-Tokyo Bay area. The highest sea level during Holocene time in Oku-Tokyo Bay has been considered to have occurred in around 6,000 yr B.P. in many previous studies. However, the revised sea levels don't support the traditional opinion as mentioned above. Namely, the possibility that the highest

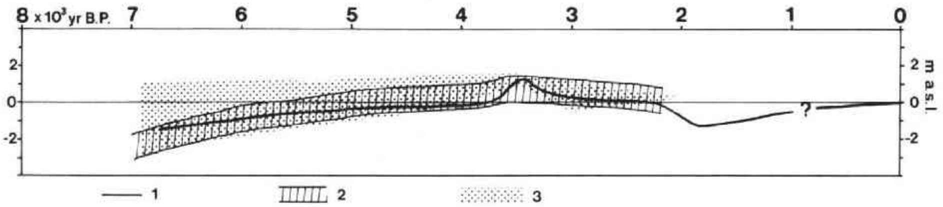


Fig. 28 Compilation of late Holocene sea-level changes curves of Matsushima Bay, Nanao-nishi Bay and Oku-Tokyo Bay.
1. Matsushima Bay, 2. Nanao-nishi Bay, 3. Oku-Tokyo Bay.

sea level during Holocene time occurred in about 3,500 yr B.P. is indicated by considering the amplification of tidal range during the Postglacial transgression.

6 Conclusion

6.1. The highest sea level during Holocene time in Japan

The three sea-level changes curves obtained from Matsushima Bay area, Nanao-nishi Bay area, and Oku-Tokyo Bay area respectively are compiled in Fig. 28. These sea-level changes curves show almost the same trend. Especialy, the highest sea level during the late Holocene is recognized at about 3,500 yr B.P. in each sea-level changes curve. The sea level at that time seems to have stood at 1.0-1.5 m above the present sea level.

Most of the previous studies have considered that the highest sea level during Holocene time in Japan occurred in around 6,000 yr B.P. Ota *et al.* (1982 and 1990) have thought that the age at the highest sea level during Holocene time was previous to 6,000 yr B.P. in the area whose uplift rate had been relatively fast, on the other hand the age was between 6,000 yr B.P. and 5,000 yr B.P. in the area whose uplift rate was relatively slow. However, in eastern Hokkaido, the Tsugaru district in northern Honsyu, and the Osaka Bay area, where uplift rate has been considered relatively slow by Ota *et al.* (1982 and 1990), no data indicating the sea levels of the days after 5,000 yr B.P. have been obtained (Matsushima 1982 ; Umitsu 1976 ; Maeda 1980). Moreover, in these areas, the Last Interglacial marine terraces are recognized at between 20 m and 70 m above the present sea level (Japan Association for Quaternary Research ed. 1987). Therefore, even if the relative sea level between 6,000 yr B.P. and 5,000 yr B.P. stood at above the present one in these areas, the sea level doesn't necessarily show the highest one during Holocene time, because the possibility that these areas have undergone the influences of uplift during Holocene time like Nanao-nishi Bay area is indicated.

On the other hand, there are some reports in the former studies suggesting that the highest sea level during Holocene time occurred in about 3,500 yr B.P. (Koba *et al.* 1982 ; Shimoyama *et al.* 1986). However, most of scholars in Japan have merely regarded these data as the regional singularity caused by crustal movement (for example, Ota *et al.* 1990). On the contrary, in this paper, the results showing that the highest sea level during Holocene time had occurred in 3,500 yr B.P. were obtained from Matsushima Bay area situated in the relatively stable zone of crustal movement by tracing the migration course of shoreline, Nanao-nishi Bay area situated in the uplift zone by eliminating the influences of crustal movement, and Oku-Tokyo Bay area situated in the area forming a bay extending far back during the Postglacial transgression by reconstructing the tidal range in the period. Therefore, it is concluded that it is quite possible that the highest sea level during Holocene time in Japan occurred in about 3,500 yr B.P.

6.2. Sea-level fall during *Yayoi* period (around 2,000 yr B.P.)

After 3,500 yr B.P., the sea level fell gradually. However, the sea level didn't fall to below the present one until 2,200 yr B.P. (Fig. 28). In Matsushima Bay area, it was clarified that the sea level had fell to 1.5 m below the present one after 2,200 yr B.P. Though the direct data indicating the sea-level fall was not obtained from the other two areas, a buried shallow valley formed during this period was found in Nanao-nishi Bay area. Moreover, the author obtained the data indicating the sea-level fall from the deposited levels and ages of mangrove peats in the Philippines and Ponape Island, Micronesia (Fujimoto *et al.* 1989 ; Fujimoto and Miyagi 1990). It is possible that the sea-level fall around 2,000 yr B.P. is an eustatic change, because it is found commonly in wide area including the different hydro-isostatic trend area.

6.3. Problems for future study

In this study, the following sea-level changes which have amplitude of about three meter were found, *i.e.*, the sea level continued to rise until 3,500 yr B.P. to 1.0-1.5 meter above the present one, after that it fell to 1.5 meter below the present one by about 2,000 yr B.P., and then it began to rise again. However, it is possible that the fluctuations which have amplitude of less than 50 cm occurred, because it is impossible to find them by the method which determines the upper limit of marine deposit, judging from the accuracy of the method. Hence, in order to find the micro-scale fluctuations, something new method has to be applied. However, the micro-scale sea-level fluctuations, which are considered to have occurred in the time scale of $10^1 \sim 10^2$ years, doesn't seem to have affected the formation of the small-scale landforms, *i.e.*, beach ridge ranges, coastal sand dune ranges, and Holocene marine terraces, *etc.*, which are considered to have been formed in the time scale of $10^2 \sim 10^3$ years. Therefore, the causes of the landforms formation and their development processes can be discussed by use of the small-scale sea-level changes clarified by this study.

On the other hand, in order to confirm the accuracy of the sea-level changes, it is necessary to clarify the sea-level changes in the relatively stabel zone of crustal movement situated in the same area of hydro-isostatic trend, for example the Korean Peninsula.

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